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Long term compressive testing of masonry – Test procedure and practical experience

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ABSTRACT: The sudden collapses in Italy (Civic Tower of Pavia 1989, Noto Cathedral, 1996) initiated the research into long term behaviour of historical masonry structures. Last decade, international ad hoc collaboration was established within several research institutes in Europe. The testing on masonry samples identified the creep behaviour as a possible cause of the collapse of historical masonry buildings. Secondly, research focused on the study of the factors affecting creep (rate of loading, stress level,..) and efforts were made to set up the most suitable testing procedures to understand the phenomenon. The gained insight in the long term behaviour and its description by means of rheological models, is validated mainly by means of long term testing, identifying significant parameters (strain rate of secondary creep phase, damage parameters. . .). This contribution merges the ample experiences gathered over a period of more than 15 years and drafts a first guideline for a common description of the test setup, testing procedure, data-acquisition and -processing.

1 INTRODUCTION

To gain more knowledge on long term behaviour of historical masonry, mostly three types of tests are performed:

- Compressive tests: monotonic uniaxial compressive tests are often used as preliminary tests, to have a first indication of the compressive strength of the material. From these tests, the peak stress and peak strain are obtained;
- Accelerated creep tests, also called step-by-step tests, short term or pseudo creep tests are carried out at constant load steps. The stress value is kept constant for a certain period and is then increased with a specific load increment. This procedure is continued until failure. These accelerated creep tests are often used instead of long term creep tests to study the creep behaviour and to examine the influence of the loading velocity on the material resistance;
- Long term creep tests. During these tests, a constant load is applied, reproducing a realistic creep phenomenon. Because of the long term nature, long term creep tests at constant load are often replaced by creep tests at increasing load steps, during which a time step of a several months is applied, sufficiently long for capturing both transient phenomena and the viscous creep phase.

In a first section of this paper, attention is paid to:

- description of the materials (brick/stone, mortar) and specimens (size, construction, storage procedure);
- experimental testing of the components: compressive and tensile tests on brick/stone and mortar;
- experimental testing of the composite masonry: monotonic tests, accelerated (or short term) creep tests, (long term) creep tests;
- data-acquisition (stress/strain, crack openings, other NDT-tests) and data-processing;
- reporting requirements.

In the following sections, links are made with the practical experience gathered at the different laboratories

on the aforementioned items to illustrate their relevance for modeling the long term behaviour of historical masonry subjected to high sustained loading.

2 DRAFT GUIDELINES

From the experiences gained at different laboratories, a general denominator within the long term testing of masonry is clearly visible. The overall (research) test campaign consists both of component testing and testing of the composite masonry. For the latter mainly 3 types of compressive tests are performed each having a different time frame and objective: monotonic compressive tests, short term or accelerated creep tests and long term creep tests. The collected information is summarized.

2.1 *Description of materials and specimens*

The description of materials and specimens is not specific for this type of masonry testing, and follows a layout similar to general tests on masonry. It covers a clear description and reporting of:

- Materials used:
  - brick/stone (type, size/layout, origin,..);
  - mortar (composition: binder type, pozzolan, w/b-ratio, sand, admixtures,. . .);
- Masonry specimens: size (cross-section, height, slenderness-ratio), thickness of mortar joints (bed/head joints), number of brick/stone layers, layout of wallet (single or multiple leaf), construction/cutting or sawing, curing/storage procedure;
- Construction conditions including relative humidity (RH) and temperature (T); parallel production of mortar samples for testing of the mortar strength at the same time as the masonry samples;
- Curing conditions of wallet and mortar samples: RH and T, period.

2.2 *Experimental testing of the components*

Testing on components is performed to obtain the general characteristics of both brick/blocks and mortar separately. In general, compressive and tensile tests on brick/stone and mortar are performed, aiming at values for the compressive behaviour f_c (compressive strength), E (Young's modulus), ν (Poisson ratio); and tensile behaviour: f_t (tensile strength). Some specific aspects are highlighted:

- Brick/stone:
  - Different sample types and sizes are used (couplet, core, prism sawn from brick) with different slenderness or height/base ratio;
  - The compressive tests on brick are performed both in head and bed joint direction in case of hand-made clay bricks;
  - Tests are performed displacement controlled (v = 1–6 μm/s);
  - In the reporting the individual results and data statistics are to be included (number of samples, average, and spread or coefficient of variation);
  - Interest is not only in the compressive strength (f_c), but also in the stress-strain relationship (and post-peak behaviour) for which the force-displacement evolution is captured with LVDT's, strain gauges;
- mortar:
  - different sample sizes are encountered: 40 × 40 × 160, 50 × 50 × 50 mm^3 or other);
  - standard compressive and 3-point bending tests are performed in general;
  - different ages at testing are often preferable to check the strength evolution to ensure testing of the composite masonry at full strength development;
- There is no general information available related to the (minimum) number of tests to be used, although often, a relatively large scatter is obtained.

2.3 *Experimental testing of masonry specimens*

Experimental testing of the long term behaviour of the composite masonry consists of three types of tests, as mentioned in the introduction:

2.3.1 *Monotonic tests*

In relation to the creep tests, monotonic compressive tests are performed to gain insight into the compressive behaviour of the composite masonry (stress-strain and post-peak behaviour) and to have a reference value for the ultimate strength.

In general following elements are addressed:

- Material characteristic: f_c, E, ν, $\sigma-\varepsilon$, for which the required data-acquisition devices are deployed: LVDT's, strain gauges, both in axial and transversal direction at all 4 faces of the wallets, in order to enable the calculation of an average deformation;
- Type of sample and size: wallets have a cross-section equal to the brick length and a slenderness or: height/base ratio of at least 2;
- Direction of testing: according to direction of bed joint or corresponding the on site load direction for specimens obtained on site;
- The test is performed displacement controlled (v = 1–6 μm/s) and under constant RH and T;
- The age at testing is chosen to ensure full hardening of the binder;
- The minimum number of tests is to be taken 3.

2.3.2 *Accelerated (or short term or pseudo) creep tests*

Short term or accelerated creep tests are performed to gain insight into the damage accumulation at different stress levels. This is used to fill out both the viscous damage (D^V) and static damage (D^S) parameters within a rheological creep model.

- Type of sample and size, age, laboratory conditions: taken equal to the layout of monotonic compressive tests;
- The initial stress level: is taken a percentage (40–65%) of the minimum or average compressive strength (f_c); successive stress increments again are a percentage (5–20%) of the same compressive strength. The duration of each stress increment is taken constant for a period, at least equal to 1.5 hours. The longer the period taken, such as 24 hours, the more clear distinction in between static and viscous damage at the subsequent stress levels are obtained and the better a tertiary creep phase can develop at the final loading step. In addition unloading steps might be included;
- Test setup: depending on the length of period at which the load is taken constant, the setup will generally change from the setup used for monotonic compressive tests towards a setup used for long term creep tests for the longer time intervals;
- The minimum number of tests is to be taken 3.
- Data-acquisition has to enable the recording of force-displacement (LVDT's, strain gauges) both in axial and transversal direction at the 4 faces of the wallets;
- A graphical presentation of the loading-path, crack-pattern and strain-time evolution is presented.

2.3.3 *(Long term) creep tests*

Long term creep tests are performed to gain insight into the damage accumulation (rate) at specific stress levels to validate the numerical (reological) modeling and give feedback to actual case studies.

- Type of sample and size, age, laboratory conditions: taken equal to the layout of monotonic compressive tests and accelerated creep tests;
- Loading path:
  - Constant stress-level: in specific cases a real creep test is performed at which a specific stress-level is applied and kept constant until failure;
  - Stepwise increased stress-level: the loading path is similar to the accelerated creep tests. The difference is the period over which a constant stress level is maintained. The latter equals at least 45 days and preferable extents to 3 months.
  - Test setup: the extended time-frame poses additional requirements to the testing equipment. In general a separate frame is required, providing sufficient strength and/or stiffness. The load is applied by means of hydraulic jacks and a displacement compensation chamber / accumulator is provided to maintain constant loading regardless the axial deformations of the specimen tested, Figure 1.

Figure 1. Creep test setup at Politecnico di Milano (left), University of Minho (middle), KULeuven (right).

- Data-acquisition has to enable the recording of force-displacement both in axial and transversal direction at the 4 faces of the wallets. Because of the lengthened time frame, generally, removable strain gauges and contact seats, glued to all sides of the wallets, are used to enable discrete acquisition of both axial and transversal displacements. Again a graphical presentation of the loading-path and strain-time evolution is presented;
- Specific reporting attention goes to the mapping of the crack pattern and monitoring of crack openings at discrete moments in time (or as function of the stress increment).

2.4 *Additional data-acquisition*

Besides conventional monitoring of stress-strain behaviour and crack opening, other NDT-tests deliver valuable information, such as: (ultra-) sonic tests or acoustic emission monitoring, see further.

3 EXPERIENCE AT POLITECNICO DI MILANO

The research into the time-dependent long term behaviour of ancient masonry started in Italy after the unfortunate collapse of the tower of Pavia (Binda et al., 1992; Anzani et al., 1993, 2003; Bda, 2007; Binda et Anzani, 1993; Mirabella et al., 1997; Pina-Henriques, 2005). Exploiting at first ancient masonry coming from ruins, several experimental procedures have been adopted to understand the phenomenon and feed various rheological models. The case of the crypt of Monza is described as an example of ample practical experience gained last decades (Modena et al., 2001).

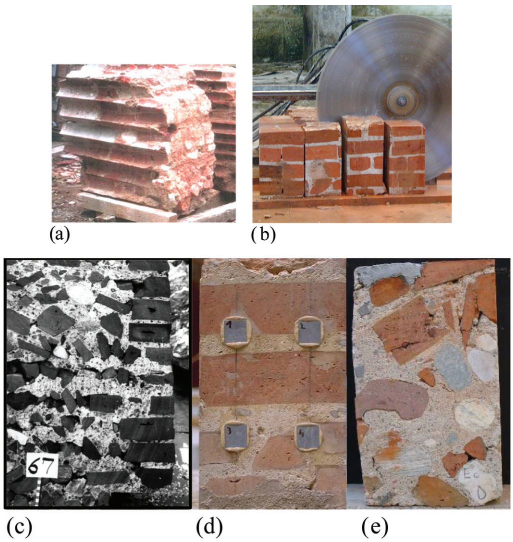


Figure 2. Removal from samples (a) and cutting prisms (b) (ir)regular layout of historical masonry walls (c–e) [source: Politecnico di Milano].

3.1 *Masonry specimens*

Performing tests on specimens from real case studies involves additional practical boundary conditions, Figure 2:

- The removal of samples on site by means of coring their perimeter, Figure 2a;
- The sawing of samples by means of a diamond saw. For the cathedral of Monza, the resulting dimensions of the prisms are $200 \times 200 \times 350\,mm^3$, Figure 2b;
- Accounting for the irregular layout of the masonry (single leaf (ir)regular – multiple leaf masonry, Figure 2c–e.

3.2 *(Preventing) monotonic compressive tests*

For the crypt of Monza, 3 monotonic compressive tests are performed to have a first indication of the compressive behaviour of the masonry, Figure 3:

- Sample size: $200 \times 200 \times 350\,mm^3$;
- Displacement controlled: $1\,\mu m/s$;
- Acquisition of horizontal and vertical displacements at all 4 faces of the sample and of the platens to enable the registration of stress-strain behaviour after peak stress;

Dealing with historical buildings puts additional pressure on the amount of original material at the disposal of the researcher. Therefore, alternatively sonic tests are carried out for non-destructive strength estimation. These sonic tests are calibrated based on (monotonic compressive) pseudo creep tests, demonstrating an acceptable correlation, Figure 4.

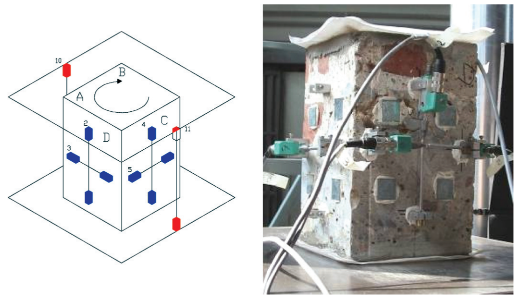


Figure 3. monotonic compressive testing – layout and data-acquisition [Source: politecnico di Milano].

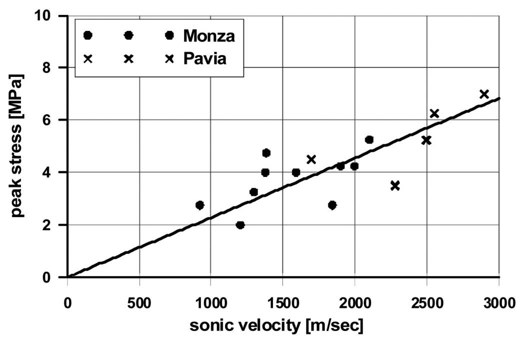


Figure 4. Correlation between sonic velocity and peak stress [source: Politecnico di Milano].

3.3 *Pseudo or short term creep tests*

Considering that long term tests require constant thermo-hygrometric conditions and especially designed testing apparatus, a more rapid and therefore more convenient testing procedure was subsequently preferred. The so called pseudo-creep tests were carried out applying the load by subsequent steps corresponding to a constant value (generally 0.25 or 0.3 MPa) kept constant for a specific time interval. Different durations of the time interval have been experimented (from 300 to about 30000 seconds (8.3 hours)) which allowed to indirectly observe the influence of the rate of loading. In fact, these tests, characterized by a regular load history, tend to simulate, by discrete load steps, monotonic tests where the load increases continuously at an equivalent rate which can be calculated. They give the opportunity to satisfactorily catch the limit between primary and secondary creep phase.

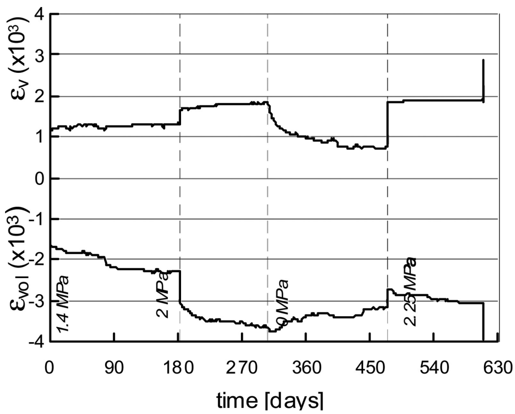


Figure 5. Long term creep test [source: Politecnico di Milano].

From the Monze crypt two series of pseudo-creep tests are performed:

- The first series of pseudo-creep tests (4 samples) had following loading path: initial stress level: 2.25 MPa (equal to 65% of the average f_c from monotic testing; the stress increment equals 0.25 MPa (7% of f_c); loading was kept constant during 5400s (1.5 h); some unloading-reloading cycles were required during the night;
- The second series of pseudo-creep tests (6 samples) had a clearly different loading path: no initial monotonic stress level was applied; the stress increment equals 0.25 MPa (7% of f_c); the different stress-levels were kept constant during 10800s (3 h).

In both cases, the constant load steps turned out to be a suitable procedure for analyzing creep behaviour. Primary, secondary and tertiary creep phases have been clearly observed, together with their relationship with the stress level, damage development being associated to an increase of the stress level.

3.4 *Long term creep tests*

Long term creep tests on 6 prisms coming from the ruins of the tower of Pavia and 1 of the crypt of Monza were performed, some of which lasted 1000 days. The latter creep test was carried out at the ENEL-CRIS laboratory (Milan) in an especially designed apparatus, in controlled conditions of 20°C temperature and 50% RH. During the 630 days test, three load increments of 1.4 MPa, 2 MPa and 2.25 MPa, respectively, and an unloading phase were applied. In Figure 5 the vertical and volumetric strain are plotted vs. time. It appears that after load removal, it took to the material more than 100 days to completely recover the accumulated creep strain.

(a) (b) (c)

Figure 6. Adobe masonry: (a) abode units; (b) mortar specimens; (c) adobe prisms [source: University of Minho].

4 EXPERIENCE AT UMINHO

4.1 *Materials and specimens*

The ongoing experimental program at the University of Minho comprises the testing of both adobe masonry and clay brick masonry specimens, which are considered to be the existing Portuguese masonry types most vulnerable to creep phenomena.

4.1.1 *Adobe masonry*

The adobe units were collected from a partial demolished building in the center of Portugal and then were cut with the approximated dimensions of $200 \times 200 \times 120\,mm^3$, see Figure 6a, in order to be directly used in the construction of the prisms to be tested under monotonic and long term loading (Oliveira et al., 2007).

The mortar composition was chosen as to be representative of mortars typically found in Portuguese adobe constructions: a lime based mortar made of hydrated lime:earth:sand in proportions of 1:1:2 (volume ratio), without any pozzolanic reaction capacity. The quantity of water added to the mixture was the quantity enough to obtain a workable mortar, following the traditional methods.

Masonry specimens were constructed with a prismatic shape, with a cross-section of $200 \times 200\,mm^2$ (one unit) and a height of approximately 400 mm, being prisms composed of 3 units and 4 mortar joints, see Figure 6c. The establishment of a maximum height/base ratio of 2 was related to limitations raised by the maximum allowable free height of the creep frames. The thickness of the joints was kept between 15 and 20 mm. During the construction of the specimens, mortar samples were colleted randomly in order to be tested later, see Figure 6b.

During the construction and the first three weeks of curing, both the mortar samples and the prisms were maintained in laboratory ambient conditions. Mortar shrinkage phenomena were mitigated by covering specimens with a wet tissue and an impermeable plastic sheet. Afterwards, specimens were kept inside a climatic chamber, where ambient conditions were

(a) (b) (c)

Figure 7. Clay brick masonry: (a) brick units; (b) mortar specimens; (c) brick prisms [source: University of Minho].

programmed for a temperature of 20°C and a RH of 57.5%, and remained there until testing.

4.1.2 *Clay brick masonry*

Aiming at obtaining representative materials, hand-made clay bricks were used, see Figure 7a. A disadvantage of this option is the variability of the geometric dimensions and the nonlinearity of the faces, which forced the cut of the bricks to build the prisms.

The mortar composition used was based on a previous study (Oliveira et al., 2006), where a low strength lime based mortar was developed. In this way, the mortar was made of binder:sand in proportions of 1:3 (volume ratio). In order to minimize the carbonatation phenomenon that may affected the strength evolution in time of newly lime based mortars, the binder was composed of 20% of lime and 80% of metakaolin (pozzolanic material).

Masonry specimens were constructed with a prismatic shape, composed of 6 layers of 2 bricks each, see Figure 7c. Geometrical limitations related to the available creep frames lead that prisms were built with a cross-section of $200 \times 200\,mm^2$ and a height of 400 mm, with the objective of having a height/base ratio around 2. The thickness of both bed and head joints was kept about 10 to 15 mm. As done before, mortar samples were collected during the construction of the prisms, in order to be mechanically characterized, see Figure 7b.

The construction and curing of the prisms was done inside a climatic chamber with a controlled temperature of 25°C and around 100% RH. The high temperature (the highest that could be reached inside the climatic chamber) and RH were intended to accelerate the curing of mortar. The mortar samples were also stored inside the climatic chamber, together with the prisms. The aforementioned temperature and humidity conditions were kept constant during the first month, being then changed to a 20°C and 57.5% R.H.

4.2 *Testing of the components brick-mortar*

All tests presented below were carried out in laboratory ambient condition under displacement control, at a rate of approximately 3 μm/s.

4.2.1 *Adobe masonry components*

The mechanical characteristics of the adobe units:

- Cylindrical cores (d = 80 mm), h/d = 2; mean $f_c = 1.1\,N/mm^2$; $E = 200\,N/mm^2$. These values are typical for hand-mad blocks made of low quality raw materials;
- Mortar prisms: $50 \times 50 \times 50\,mm^3$, $n_{samples} = 9$; mean $f_c = 1.0$ MPa at age of 90 days (approximately same age of masonry samples at testing).

4.2.2 *Clay brick masonry*

The mechanical characteristics of the clay brick masonry (Oliveira et al., 2006):

- Clay bricks tested according to head joint (flatwise): mean $f_c = 7.7$ MPa and according to bed joint (lengthwise) mean $f_c = 10.2$ MPa. Same trend is visible for the Youngs' modulus: mean $E = 906$ MPa according to head joint and $E = 1377$ MPa according to bed joint). However, high coefficients of variation are encountered.
- Mortar prisms: $50 \times 50 \times 50\,mm^3$, mean $f_c =$ 2.0 MPa (28 days), 2.2 MPa (90 days); 1.8 MPa (180 days) illustrating that a further increase in strength as function of time seems not to take place.

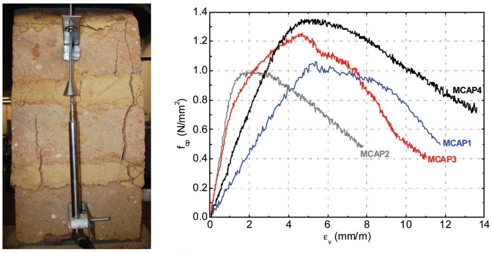
4.3 *Testing of masonry specimens*

4.3.1 *Monotonic compression tests*

Monotonic compression tests were carried out on both masonry types, in order to provide a reference value of the compressive strength of the masonry. This parameter was later used to estimate the load increments to be applied during the short term and long term creep tests. The monotonic tests were carried out in laboratory ambient conditions under displacement control, whereas the short term and long term creep tests were performed inside the climatic chamber.

4.3.1.1 Adobe masonry

- $n_{samples} = 4$, age at testing: 80 days;
- data-acquisition: axial displacements – 4 LVDT's connected to the prism's faces; 3 LVDT's connected to the platens to trace the full stress-strain behaviour of the prisms including the post-peak behaviour;
- mean $fc = 1.2$ MPa; $E = 630$ MPa;
- the stress-strain behaviour demonstrates large scatter, Figure 8b;
- close to failure, the crack pattern is basically constitued by vertical cracks in all faces, Figure 8a.



(a) (b)

Figure 8. Adobe masonry tests: (a) crack pattern at failure; (b) structural response in terms of stress-strain curves.

4.3.1.2 Clay brick masonry

- Age at testing: 28, 90 and 180 days;
- Displacement controlled: v = 6 µm/s;
- Data-acquisition: identical to adobe masonry;
- Mean f_c = 5.6 MPa (28 days), 5.3 MPa (90days), 5.7 MPa (180 days), again illustrating that a further increase in strength as function of time seems not to take place.

4.3.2 *Short term creep tests*

The short term creep tests are performed within a climatic chamber, in which the samples are stored for curing. The load path used: start at 40% of mean f_c; load increment of 10% of mean f_c kept constant during 24 hours, increased until collapse. The test setup, Figure 1b, allows simultaneous testing of 2 prisms, provided that a rigid steel plate is placed between both samples. The top plate is hinged while the bottom plate restrained all movements. Load application was controlled trough a pressure gauge and both axial and transversal deformations were measured on each face of the prisms with a removable strain-gauge. Measurements were always performed by the same person to avoid reading errors ascribable to the operator. In the reporting, both the loading path and strain-time diagrams are given, Figure 9.

4.3.3 *Long term creep testing*

The test-setup for the long term creep tests is identical to the short term creep tests. The load path used: initial stress level: 40% of mean f_c (at 180 days for clay brick masonry); load increment of 20% of mean f_c with duration of 45 days for the first two increments and 90 days for the subsequent increments. Data-acquisition and reporting is done in an equal way compared to short term compressive testing.

5 EXPERIENCE AT KULEUVEN

5.1 *Materials and specimens*

The ongoing experimental program at KULeuven focuses on newly constructed samples at which the components are chosen to be representative for historical brick masonry encountered in Belgium. One single type of brick is combined with different types of mortar: cement mortar, hydraulic lime mortar, hybrid mortar and air-hardening lime mortar. The purpose is to investigate the effect of differences in stiffness between brick and mortar on the long term creep behaviour.

The handmade clay bricks, type "Spanish red" from Wienerberger have dimensions 188*88*48 mm. The mortar compositions are indicated in Table 1. In order to account for the effect of carbonation of the air-hardening lime mortar, a part of the mortar and masonry specimens is subjected to accelerated carbonation curing conditions.

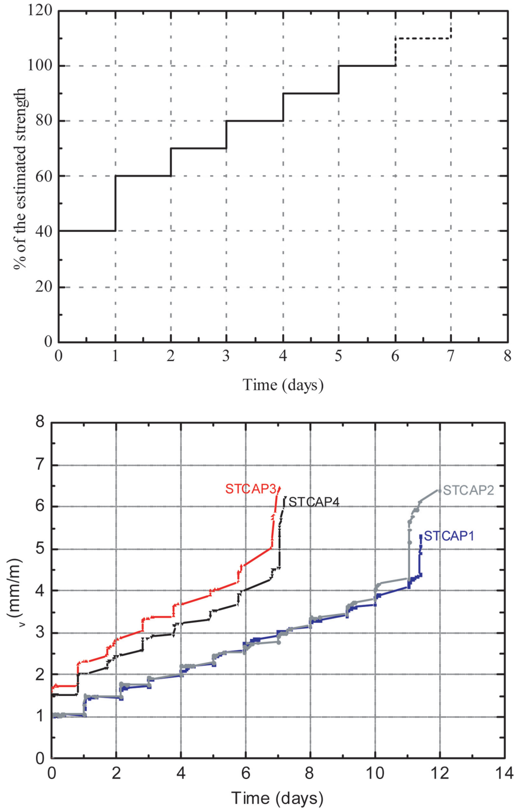


Figure 9. Short term creep test: Loading path – strain-time diagram.

5.2 *Masonry prisms*

Masonry specimens were made by constructing small prisms with a base of 290 × 190 mm (three bricks)

Table 1. Mortar compositions.

Mortar	Sand Riversand [kg]	Cement CEM42.5 [kg]	Hydr. lime [kg]	Unilit [kg]	Water [l]
Cement	30	7.8	–	–	5.1
Hydraulic lime	–	–	–	30	4.3
Hybrid	30	2.6	4.48	–	4.0
Air hardening lime mortar	30	–	5.04	–	6.8

Legend: Unilit: sand-hydraulic lime mixture.

and 15 layers in height. A mortar joint thickness of 1 cm is applied, resulting in prisms with an approximate height of 85 cm. Consequently, a uniform stress distribution could be assumed in the middle of the specimens. The more recent prisms with air-hardening lime mortar were constructed with smaller dimensions of 190×190 mm (two bricks) and a height of approximate 60 cm, which corresponds to 10 layers of brick. This smaller specimen size was chosen due to equipment restrictions – larger specimens require heavier jacks and for each long term test, a separate hydraulic test device needs to be made. The slenderness ratio is kept constant.

During the construction of the prisms, mortar beams ($40 \times 40 \times 160\,mm^3$) are made from the same mortar batch as the masonry. The wallets are constructed and pointed with the same mortar in order to obtain a homogenous mortar composition. Before construction, the bricks are pre-wetted as they are rather porous, to avoid the absorption of large amounts of water from the mortar.

The prisms are stored in an acclimated room at 20°C and around 60% RH. until testing. For the specimens with cement mortar, initially, storage in a room with higher relative humidity would be better, but due to the specimen's dimensions, this possibility was not an option. The prisms with cement and hybrid mortar are cured for 28 days before testing. The prisms with lime mortar are cured for at least three months prior to testing.

5.3 *Testing of the components brick-mortar*

The brick as well as the mortars were subjected to compressive tests and 3-point bending tests, Table 2. The 3-point bending test is performed instead of a direct tensile test or a Brazilian test as experience has shown that 3-point bending tests are easier to perform and give a smaller spread on the results. No relation between these data and the results from long term compressive testing of masonry has been established yet.

Table 2. Results of compressive tests and 3-point bending tests on brick and mortar specimen.

Samples	Tests performed and material characteristics derived
Brick :	Compr. test (f_c,b;E;ν) and 3-point bending test (f_t,b) $f_{c,b} = 9.97 \pm 2.24\,N/mm^2$; $E = 1314\,N/mm^2$; $\nu = 0.10$; $f_{t,b} = 3.12 \pm 0.47\,N/mm^2$(20)
Mortar:	Compressive tests ($f_{c,m}$); 3 point bending tests ($f_{t,m}$) – air hardening lime: $f_{c,m} = 0.79 \pm 0.09$ MPa(10); $f_{t,m} = 0.52 \pm 0.03$ MPa(5); E = 100 MPa(2); – hydraulic lime: $f_{c,m} = 4.47 \pm 0.28$ MPa(10); $f_{t,m} = 1.34 \pm 0.11$ MPa(5); E = 532 MPa(2); – cement: $f_{c,m} = 34.5 \pm 3.02$ MPa(10); $f_{t,m} = 5.82 \pm 0.24$ MPa(5); $E = 3325 \pm 1643$ MPa(10); – hybrid lime/cem: $f_{c,m} = 4.20 \pm 0.90$ MPa(12); $f_{t,m} = 1.13 \pm 0.24$ MPa(6); $E = 235 \pm 190$ MPa(10);

Legend: presentation of test results: average value±standard deviation (no. of samples).

5.4 *Testing of masonry specimens*

5.4.1 *Monotonic compressive tests*

Monotonic compressive tests are performed, displacement controlled ($v = 2\,\mu m/s$) to gather information on the compressive behaviour of the different masonry types. The stress and strain evolutions are registered, so that the compressive strength (f_c), Young's modulus (E) and Poisson's ratio (ν) can be calculated. During the test, the strain evolution is measured with 8 LVDT's, one horizontal and one vertical on each side of the specimen. The results are represented as a stress-strain plot.

5.4.2 *Short term creep tests*

The short term creep tests are performed within laboratory conditions (RH = 65%, T = 20°C). The test setup and data-acquisition are equal to the monotonic compressive tests (in contrast with the setup used at Minho). The load path used: start at 50–60% of mean f_c; load increment of 5% of mean f_c kept constant during at least 2 hours, and increased until collapse. The periods of constant load are required to limit the full test duration within the period of one day.

Three accelerated creep tests were performed for each type of mortar. In the reporting, both the loading path and strain-time diagrams are given, Figure 10, an example outcome obtained on the hydraulic lime mortar columns.

The short term creep tests are generally preformed to obtain parameters to describe the damage evolution of the masonry. Within this test setup however,

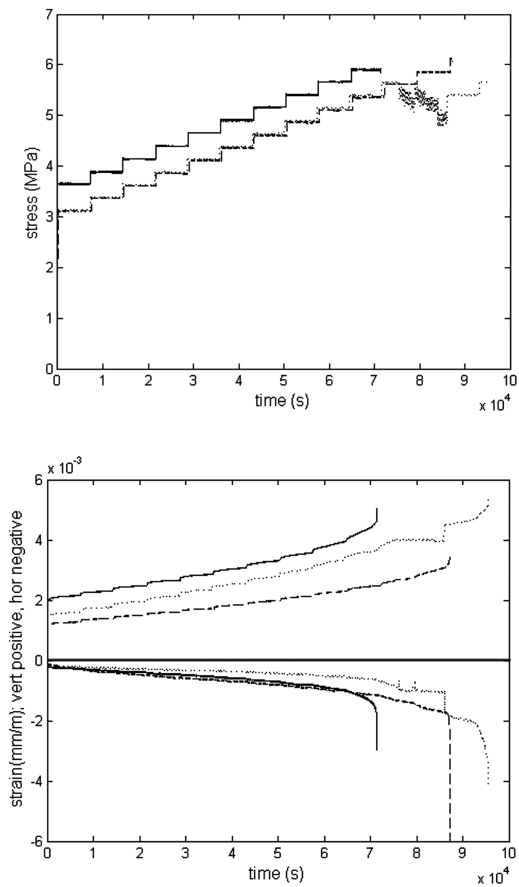


Figure 10. Short term creep tests – stress-time and strain-time diagram.

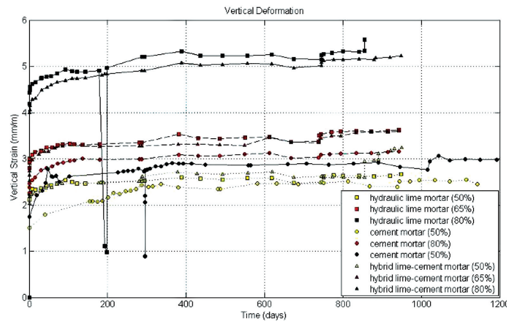


Figure 11. Results of ongoing long term creep test on masonry prisms with three types of mortar composition.

the length of the constant stress steps is not sufficient to obtain an equivalent behaviour which is obtained during long term creep (tests) and often, failure of the specimen is reached during stress increase (Verstrynge, 2008c).

Secondly, the data processing is complicated by the distinction which has to be made between the elastic and the time-dependent strain. The evolution of the damage on the elastic strength parameters is not so easy to follow as only small stress increments, and related very small strain increments, are available for the calculation of the elastic modulus. Therefore, also cyclic accelerated creep tests will be incorporated within the extension of the test program in the near future.

5.4.3 *Long term creep tests*

The long term creep tests are performed under constant climatic conditions (RH = 65%; T = 20°C). For each specimen, a separate test device is build, using a hydraulic jack and an accumulator to correct small deformations. The deformations are measured by means of a removable, mechanical strain gauge at least every month and presented in strain-time graphs, see for example Figure 11. For each mortar type, three prisms were tested.

For two wallets, an unloading and reloading cycle was included. The unloading revealed a significant portion of non-reversible deformation. After reloading, the strains reached the original level again. In relation with the different types of mortar used, it can be stated that the behaviour of the different samples is quite similar. Also in the secondary creep phase, a difference in speed of vertical deformations is hardly noticeable. One could even state that the lower stress levels only exhibit a very limited creep behaviour. The latter demonstrates that probably higher stress levels are required to enforce creep behaviour within an acceptable test period. The constant stress levels maintained during the long term creep test are initially 50, 65 and 80% of f_c.

Because of the very long duration of the tests and the difficulty in monitoring the small deformations in an accurate way over a long period of time, long term creep tests at constant load are often replaced by creep tests at increasing load steps, during which a time step of at least 2 months is applied.

5.5 *Data-acquisition – model parameters*

Considering the above discussed types of tests, the most important data recorded during the experiments are the evolution of stresses and strains. The stress is directly recorded during the test for the monotonic compressive tests and accelerated creep tests or calculated from the pressure in the hydraulic jacks during the long term creep tests. The deformations are recorded with LVDT's (one horizontal and one vertical on each side of the specimen) for the two types of short term tests. All data are saved as data-files and first of all processed with excel-sheets. There from, parameters

and extreme values can be calculated, which are used for further analysis and modeling with Matlab (The MathWorks, version R2007a).

For the long term creep tests, the same procedure is used to process the strain data, but the deformations are measured with removable, mechanical strain gauges (demec-measurement) and the data-sheets are extended after each measurement. Experience from the ongoing long term creep tests have shown that it is not always possible to monitor the deformations with enough accuracy as very long test durations and very small strain increments are concerned. Secondly, the fixed measuring points are not always useable after the appearance of cracks and the monitoring of the deformations when the specimen is close to failure can cause problems.

Therefore, two additional monitoring systems will be used during future long term creep set-up:

- Firstly the possibility is provided to switch on a permanent strain monitoring system for more accurate strain monitoring during stress increase;
- Secondly, acoustic emissions are monitored periodically during the experiments. The acoustic emission technique is a non-destructive technique which detects and locates damage at the moment of occurrence. Acoustic emissions (AE) are high frequency transient sound waves, which are emitted by the material during local stress redistributions caused by structural changes, such as crack growth. The advantage of this technique is that damage is detected at the moment of occurrence and is monitored over a certain area of the specimen and not only linearly, between two fixed points as is the case with demec measurements. The applicability of this monitoring technique for creep deformation in masonry has already been tested (Carpinteri, 2007; Verstrynge, 2008a,b) and appears to be promising.

6 DISCUSSION

A clear distinction has to be made in between the actual testing of masonry from on site and newly built masonry wallets.

In the first case, interest is in the actual long term behaviour of the masonry composite. For that reason, the mechanical tests on the components are often not included in the test campaign.

In the other case, the initial material is largely available and the focus of the research is not only on the assessment of the actual time-dependent behaviour of the composite masonry but also on the modeling and numerical simulation. This is the reason for which tests on the components brick/stone and mortar are performed as well. These are used to link the behaviour of the components with the overall behaviour of the masonry composite and the numerical modeling of the time-dependent behaviour.

7 CONCLUSION

From the experiences encountered during several years and at several research institutes, it became evident that historical masonry subjected to persistent loading demonstrates time dependent behaviour. Experimental procedures were adopted, revised and refined to induce the creep behaviour and creep-induced damage in laboratory. At this moment in time, sufficient experience is available to proceed towards a guideline in which the gained experience is translated into general procedures to be accounted for within the experimental testing. This contribution is a preliminary reflection as a starting point of the main items that are to be covered.

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